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Current controller based Power Management Strategy of Grid Connected Parallel Inverters for Distributed Generation Applications

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Abstract
To lift up the dexterity of distributed generation system solitary option is parallel inverters. This paper contemplates two novel current control strategies of parallel inverters consociate to the grid. Two DG sources PV, Fuel cells feeds the DC voltage to two parallel inverters connected to the grid. PI Current controller, ramp time current controller based design methodologies for the 3phase inverters is presented. Without communication between parallel inverters these two methods are having the capability of load following and stability. Simulations studies are carried out to investigate the active and reactive power management of the grid connected PV, Fuel cell based parallel inverters.

Keywords: *distributed generation, parallel inverters, micro grid, PI current controller, ramp time current controller, PV cell, Fuel cell.*

Nomenclature

DG	Distributed Generation
PV	Photo Voltaic
PQ	Real reactive power
VF	Voltage frequency
P-F	Real power – frequency
Q-V	Reactive power-Voltage
PI	Proportional Integral
DC	Direct Current
AC	Alternating current
L_C	Filter inductance
E	Amplitude of the sending end voltage
Φ	Angle of the sending end voltage
K_P & K_i	Gain of proportional, integral controllers

1. Introduction
The major part of electrical network is based on centralized system only, but centralized system suffers from many problems for example congestion and losses in transmission lines, stability issues etc are the main problems. To avoid all these problems the only option is distributed generation, by focusing on renewable sources scattered over a wide land is a viable solution. Inverter based DG sources are the eye candy to both the public and government. Even in the grid connected mode or islanded mode inverters play a key role so an efficient control techniques are needed to manage real and reactive powers even in grid connected, islanded modes. Single DG unit is not enough to compensate the load , so in order to accommodate much load one of the option is DG source based parallel inverters. This paper paying attention towards the power management techniques of dg source based parallel inverters.

Several control strategies such as PQ, VF, P-F & Q-V Droop, current control methods are used for parallel inverters. PQ , current control strategies are best suited for grid connected operation, but in islanding operation there is a necessity to control voltage and frequency of the micro grid along with active and reactive powers , So in islanding mode real power- frequency drooping, reactive power-voltage drooping methods are suitable, but these are best suited for medium and high voltage micro grids, for low voltage grids there is a necessity to adopt a control technique which is quite opposite to the conventional drooping that is opposite droop with virtual output inductance method, this virtual output inductance method is considered as an effective method to reduce the circulating current and stability of the micro grid system is also improved[9]. Along with the droop control method current and power controller method is also introduced to control parallel connected inverters fed with DG sources, in this paper two current loop control methods are proposed. PV, Fuel cells are the dc voltage sources that can be connected to electric power networks through power conditioning units such as dc/ac inverters [4]. The output voltage of both PV, Fuel cell is a function of load. The boost DC/DC converter adapts the PV, fuel cell output voltage to the DC bus voltage and the power controller helps to regulates the real, reactive power output according to the load. Three current controllers [6] PI, Hysteresis, ramp time controllers are there in the literature , hysteresis current control is fast and robust but has undesirable harmonics due to its variable switching frequency nature, over the past decades, many current control have attempted to find a current control that can deliver the advantage of both control techniques [5][1]. Ramp time current control is

one of the outcomes from such kind of research. Ramp time is claimed to be able to give a fast response near to the switching frequency [6]. PI current controller is commonly used in many applications due to its simplicity, creating less distortion in the output current. This PI controller operates by transforming three phase AC current I_a ,I_b , I_c in the stationary frame into the DC components I_d, I_q in the rotating frame. This will allow the associated PI steady state error in the AC applications to be eliminated and also provides independent control of injected active and reactive power into the grid [3], in the synchronous frame d and q components of inverter output current are regulated using two PI regulators [8]. This paper evaluates the performance of dq transformed two loop PI type , ramp time current control schemes used as the control strategy of inverters which are connected to DG sources. Figure. 1 shows the overall electric circuit diagram of the proposed system, Figure 2 shows the example of a smart micro grid.

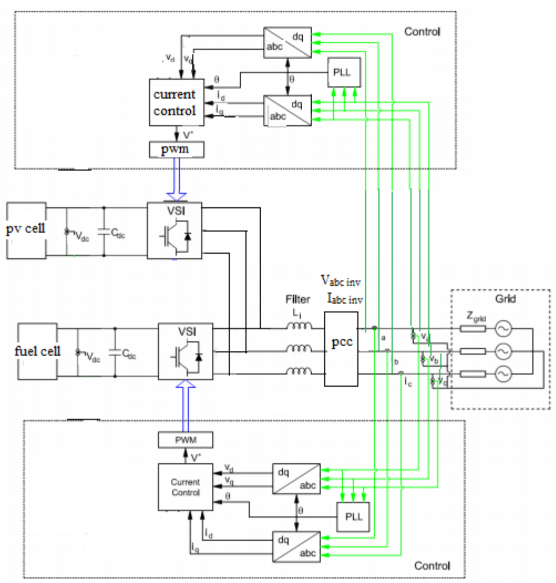

Figure.1 Overall electric circuit of the proposed system

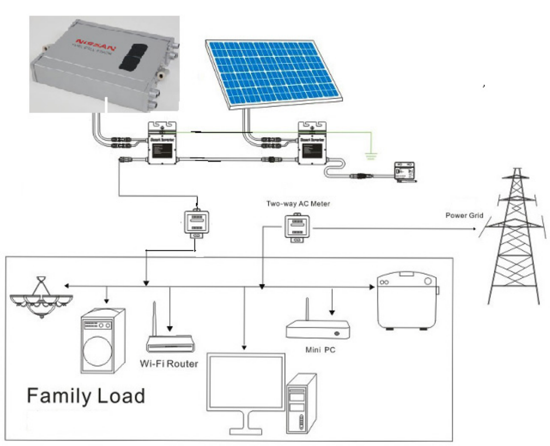

Figure. 2 Real life diagram of smart micro grid

The entire paper is organized as follows, Section 2 shows the PI based current control technique and its time response for step input, stability analysis with bode plot is performed, section 3 shows the ramp time current control technique and its time response for step, stability analysis with bode plot is performed . Section 4 explores the overall control system of the inverter and control of power section 5 shows the simulation results of parallel inverters with two current control techniques.

2. Current control loop with PI controller method:

Current control loop with PI controller is used to control the circulating currents of the inverters which are connected in parallel. The differential equations of the compensating currents in dq frame is [7] explained by the below equations (1) & (2).

$$L_C \frac{di_{cd}}{dt} = \omega L_C i_{cq} - d_{nd} V_{dc} + V_{dn} \quad (1)$$

$$L_C \frac{di_{cq}}{dt} = -\omega L_C i_{cd} - d_{nq} V_{dc} + V_{qn} \quad (2)$$

The output voltages of the voltage source inverter on dq frame is

$$V_d = d_{nd} V_{dc} \quad (3)$$

$$V_q = d_{nq} V_{dc} \quad (4)$$

Substituting V_d & V_q in equations (1)&(2) it gives the voltage at point of common coupling on dq frame.

$$V_{dn} = L_c \frac{di_{cd}}{dt} - \omega L_c i_{cq} + V_d \quad (5)$$

$$V_{qn} = L_c \frac{di_{cq}}{dt} + \omega L_c i_{cd} + V_q \quad (6)$$

On the dq frame, the voltage on d axis and q axis at point of common coupling are equal to $|V|$ and 0. The output signal of the system on d- axis and q- axis (V_d and V_q) are

$$V_d = L_c \frac{di_{cd}}{dt} \quad (7)$$

$$V_q = L_c \frac{di_{cq}}{dt} \quad (8)$$

The system to design the PI controller for two current loops can derive from equations (7) & (8) by applying Laplace transformation and simplify the same then

$$\frac{i_{cd}}{V_d} = \frac{i_{cq}}{V_q} = \frac{1}{sL_c} \quad (9)$$

In terms of proportional and integral constants direct axis voltage and quadrature axis voltages are shown in equations (10) & (11).

$$V_d = K_p \tilde{i}_d + K_i \int \tilde{i}_d .dt \quad (10)$$

$$V_q = K_p \tilde{i}_q + K_i \int \tilde{i}_q .dt \quad (11)$$

By simplifying the above two equations

$$\frac{V_d}{\tilde{I}_d} = \frac{V_q}{\tilde{I}_q} = \frac{K_p s + K_i}{s} \quad (12)$$

By simplifying the equations (9) & (12) it is possible to draw the current control loops in d axis and q axis.

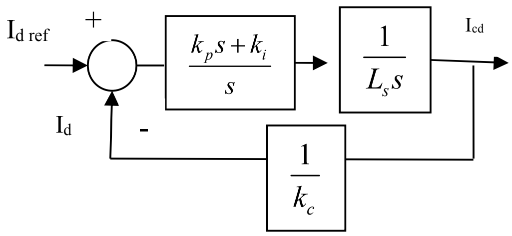

Figure. 3 direct axis current control loop with PI controller method

Figure. 3 shows the direct axis current control loop with PI controller method, The same loop is repeated for quadrature axis current controller with PI controller method but here the parameters I_{cd} is replaced by I_{cq} , $I_{d\,ref}^{*}$ is replaced by $I_{q\,ref}^{*}$.

In this system $K_P=4$, $K_I=4000$ & $L_C=1.5*10^{-3}$ is considered according to those values the system function with the designed PI controller is

$$\frac{I_{cd}}{\widetilde{I}_d}=\frac{2.66*10^3 s+2.66*10^6}{s^2+2.66*10^3 s+2.66*10^6} \tag{13}$$

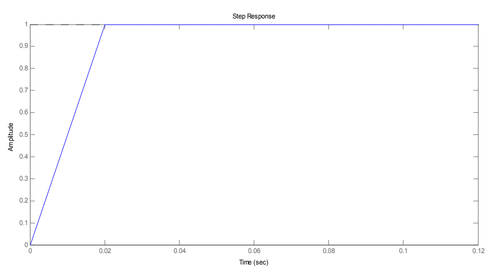

Figure. 4 step response for the designed pi current controller

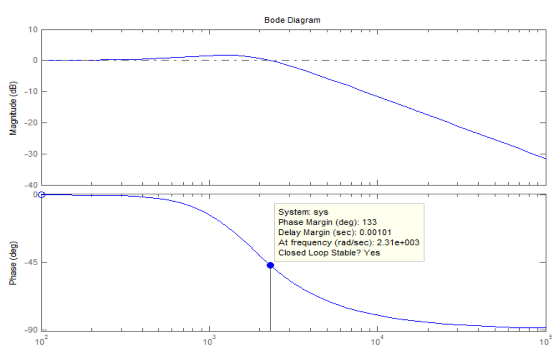

Figure. 5 bode plot for the pi controller based current control technique

Figures 4 and 5 shows that the system may settle to unit step response within a short span of time and from bode plot it was clear that closed loop stability of the considered system is also good enough to apply for distributed generation applications.

3. Current control loop with ramp comparison method:

Based on the state averaging technique the average value of the switching function in a switching period is [2]

$$\left(d_k^*\right)_{avg}=\frac{i_{ck}}{v_{tri}}, k=1,2,3 \tag{14}$$

I_{ck} is the control signal and V_{tri} is the amplitude of the carrier signal, converting the modulating signal from abc to dq quadrants.

$$\begin{bmatrix} i_{cd} \\ i_{cq} \\ i_{co} \end{bmatrix}=T_{abc/dq}\begin{bmatrix} i_{c1} \\ i_{c2} \\ i_{c3} \end{bmatrix} \tag{15}$$

I_{cd} & i_{cq} are the control signals in dq frame & $i_{co}=0$ for balanced system. K_{pwm} is the gain of the pulse generator, which is the ratio of DC bus voltage to the amplitude of the carrier signal , $G_{ACR}(S)$ is the PI controller

$$G_{ACR}(s)=\frac{k_p s+k_i}{s} \tag{16}$$

K_c is the current transducer ratio

The overall transfer function of the current control loop can be

$$T_c(s)=\frac{P_{1c}\Delta_{1c}}{\Delta_c} \tag{17}$$

Where

$$P_{1c}=G_{ACR}K_{PWM}\cdot\frac{1}{(R_S+L_S s)} \tag{18}$$

$\Delta_{1C}=1$,

$$\Delta_C=1+G_{ACR}\frac{k_{pwm}}{k_c(R_s+L_s s)} \tag{19}$$

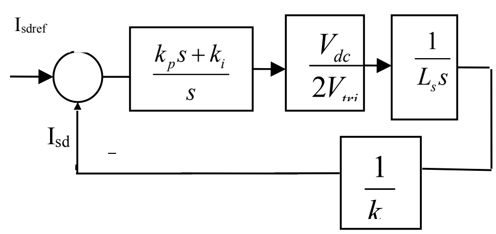

Figure. 6 Block diagram of the direct axis current loop controller of the inverter using ramp comparison method

The circuit which is shown in figure. 6 is same as for quadrature axis current loop instead of direct axis reference current here reference current will consider as the quadrature axis.

Ramp time current controller utilizes the information from its own output that is i_{sd} and compares the i_{sd} with i_{sdref} to obtain the next switching instance. This ramp time current controller is useful to achieve zero average current error, fixed switching frequency.

Ramp time current controller changes the value of next ramp time, so that next excursion time is equal to the half switching period. Due to this ramp time controller inverter switches at a fixed switching frequency and reduces the average current error to zero [10-11].

$$\frac{I_{sd}}{I_{sd\_ref}}=\frac{9.33*10^2 s+9.33*10^5}{s^2+933s+933333} \tag{20}$$

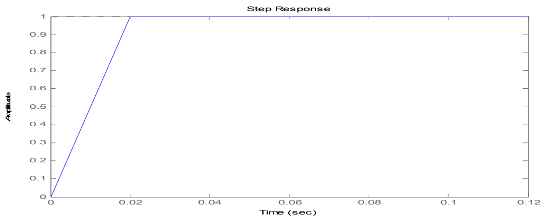

Figure.7 step response of the system for the designed ramp time current controller

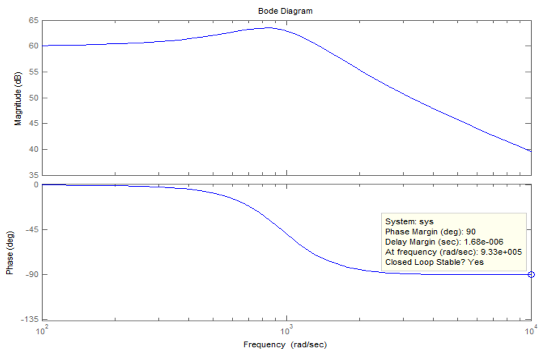

Figure.8 bode plot for the ramp time current controller technique

From figures 7 & 8 the ramp time current controller also attains step response within a very short duration of time and from bode plot it was clear that closed loop stability of the considered system is also good enough to apply for distributed generation applications.

4. Control of power:

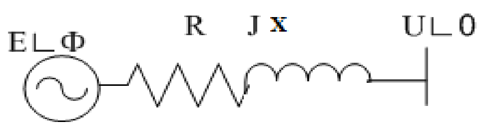

Figure. 9 power flow between a voltage source and grid

$E\angle\phi$ is the source voltage, I_0 is the inverter output current, $U\angle 0$ is the utility grid through a coupling impedance Z=R+JX as shown in figure. 9

The real and reactive powers delivered to the utility grid are

$$P = \frac{UE}{Z}Cos(\theta_z - \Phi) - \frac{U^2}{Z}Cos(\theta_z) \qquad (21)$$

$$Q = \frac{UE}{Z}Sin(\theta_z - \Phi) - \frac{U^2}{Z}Sin(\theta_z) \qquad (22)$$

$$Z = \sqrt{R^2 + X^2} \qquad \& \qquad \theta_Z = Tan^{-1}\frac{X}{R}$$

Real and reactive powers delivered to the grid are determined by the amplitude and angle of the sending end voltage, i.e the output voltage of the inverter.

Suppose if the desired values of real and reactive powers are given the values of E and ϕ can be determined from equations (21) & (22).

$$E = \left[\frac{Z^2[P^2+Q^2]}{U^2} + U^2 + 2PZCos(\theta_z) + 2QZSin(\theta_z)\right]^{\frac{1}{2}} \qquad (23)$$

$$\Phi = \theta_z - Cos^{-1}\left[\frac{ZP}{UE} + \frac{UCos(\theta_z)}{E}\right] \qquad (24)$$

The corresponding dqo component values of the voltage can be obtained through abc/dq transformation as

$$\begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} = T_{abc/dq}\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = T_{abc/dq}\begin{bmatrix} E\angle\Phi \\ E\angle\Phi - 120^0 \\ E\angle\Phi + 120^0 \end{bmatrix} \qquad (25)$$

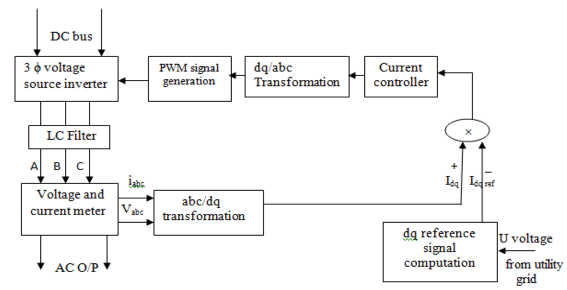

Fig. 10 Block diagram for overall control system of the inverter

Figure 10 shows the block diagram of overall control system of the inverter. Here dq reference signal computation block used to generate the dq reference current , abc/dq transformation block is used to produce the direct and quadrature axis current . The inner current controller block is used to produce the dq control signals from both the inputs , which are converted back into the control signals in abc coordinates through dq/abc transformation. These are used to modulate to produce proper pulses for the inverter switches.

5. Simulation results:

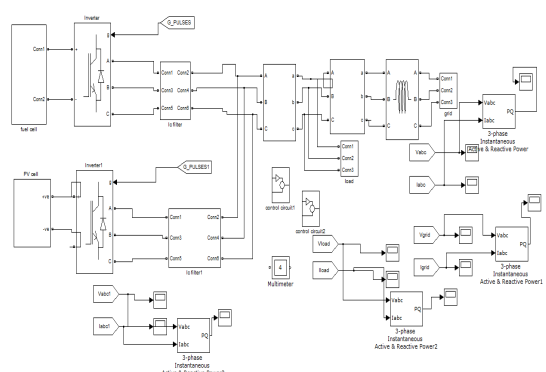

Figure. 11 shows the simulation diagram of the proposed system

This section shows the simulation of results of both the controllers when applied to DG based parallel inverters connected to the grid. Figure 11 shows the simulation diagram of the proposed system.

PV cell, Fuel cell are the two DC voltage sources used as DG units in this system, to change these two DG's output voltage to the desired inverter input voltage and smooth the two DG's output current need is there to adopt a

DC/DC boost converter. Each 35kw rated PV, Fuel cells are adopted for this study, the PV, Fuel cell output voltage is 400 volts , boost up to 700 volts using DC/DC converter, Here the controller for the converter is used to regulate the DC bus voltage with in a desirable range. The output voltage of the DC/DC boost converter is fed to DC/AC inverter. Through the point of common coupling the inverter is connected to the grid, two RL loads are connected at the point of common coupling. The inverter is always maintains the output voltage according to the reference value and at the same time inner current control loop is used to avoid the circulating currents of both the parallel inverters.

Simulation results of PI current controller based system:

Figure 12 shows the load voltages and current of two different RL loads, here 20kw real, 0.5kvar inductive load is there from 0sec to 0.5 sec and one more load of same rating is switched on from 0.2sec and 0.3 sec.

Figure 13 shows the overall current consumed by the load is around 50 amps at 0.2 sec's current consumed by the load is suddenly increased to 100 amps due to the sudden increment of load from 0.2sec to 0.3sec.

Figure 14 shows the real power 20kw and reactive power 0.5 kvar consumed by the load due to the sudden increment of load at 0.2 sec's real and reactive power consumed by the load also increased to 40kw , 1kvar according to the variation of load. Due to the sudden increment of load at 0.2 sec's PI controller trying to get smooth variation of power & to maintain stability.

Figure 15 shows the current injected to the grid, because here the connected load is less than the generated power that's why surplus power is injected into the grid.

Figure 16 shows the real and reactive power injected into the grid but some distortions are there because when compare with ramp time control PI controller is not able to follow the reference exactly.

Figure 17 shows the current output from inverter1, Figure 18 shows the output current from inverter2.

Figure 19 shows the real and reactive power supplied by inverter1; Figure 20 shows the real and reactive power supplied by inverter2.

Figure 21 shows the overall output voltage supplied by both the inverters here the output voltage is same because the two inverters are connected in parallel.

Figure 22 shows the overall current supplied by both the inverters; here inverter1 and inverter2 output current will get added due to the parallel connected system.

Figure 23 shows the overall output power supplied by both the inverters. But this PI controller is not able follow the exact reference that's why at the time of sudden increment of load some fluctuations are there in the output power supplied by both the inverters. But this will clear with the ramp time controller.

Figure 24 shows the THD of the load current at the time of sudden increment of load, here the total harmonic distortion at the time of sudden increment of load is also very less.

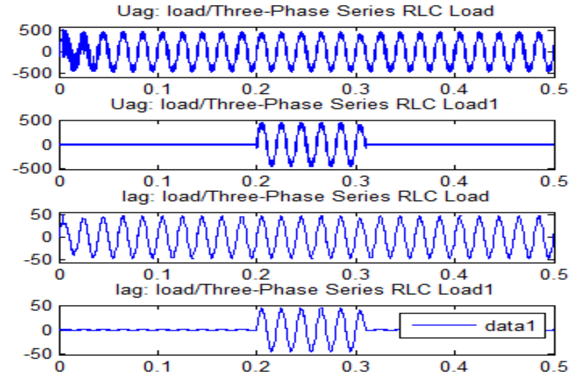

Figure. 12 load voltages and currents of two different RL loads

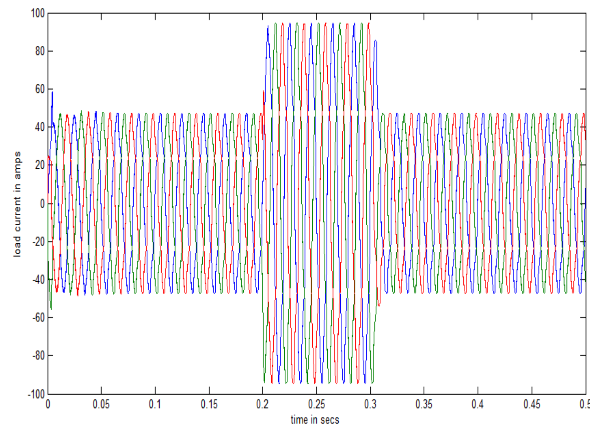

Figure. 13 overall current consumed by the load

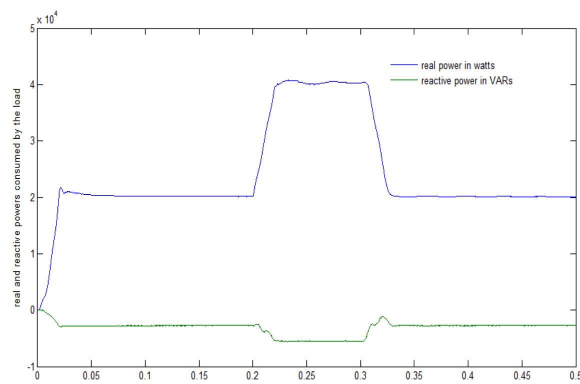

Figure. 14 Real and reactive powers consumed by the loads

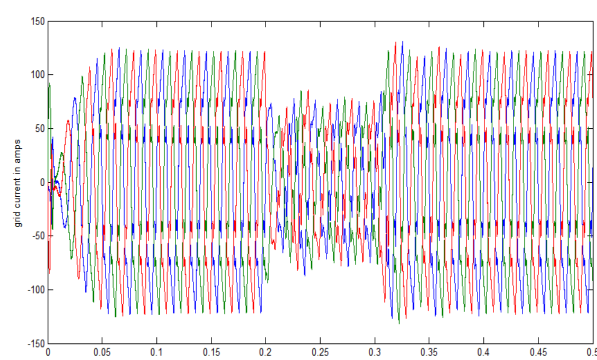

Figure. 15 current injected to the grid

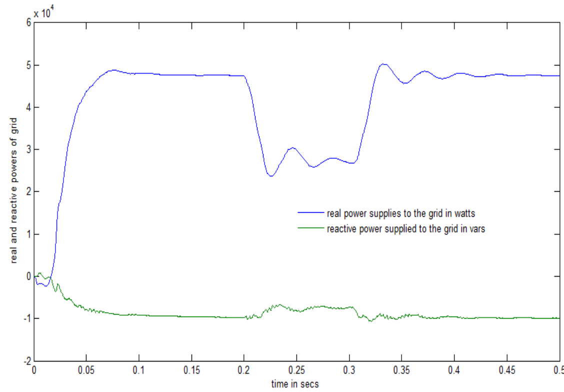

Figure. 16 Real and reactive powers injected to the grid

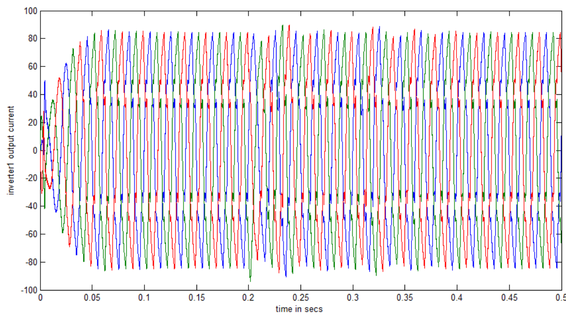

Figure. 17 current output from inverter1

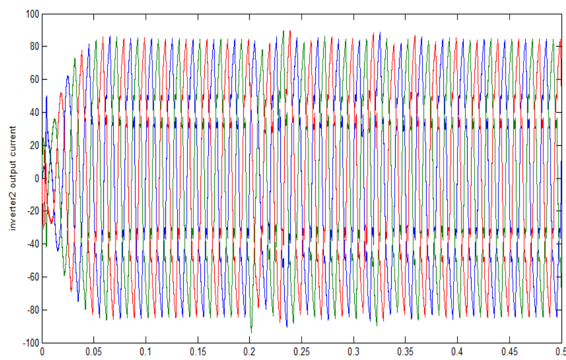

Figure. 18 inverter2 output current

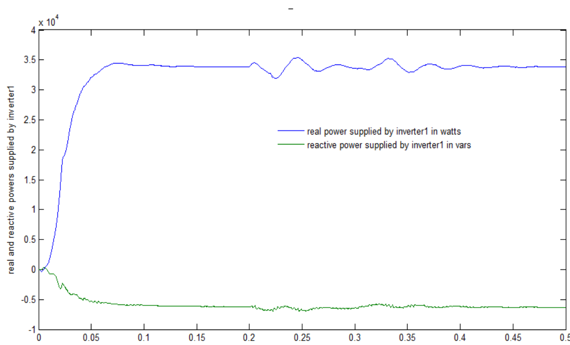

Figure. 19 real and reactive powers supplied by inverter1

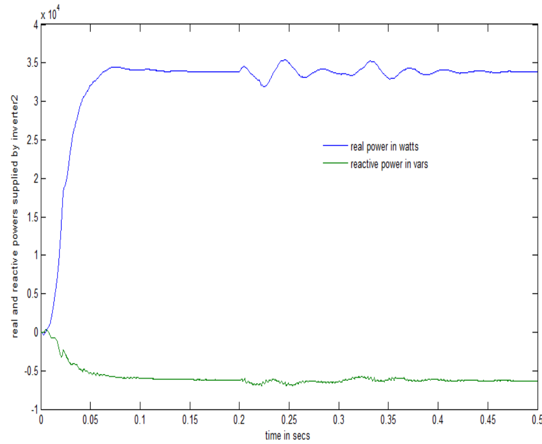

Figure. 20 real and reactive powers supplied by inverter2

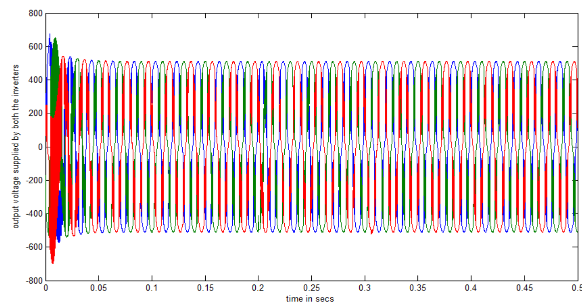

Figure. 21 output voltage supplied by both the inverters

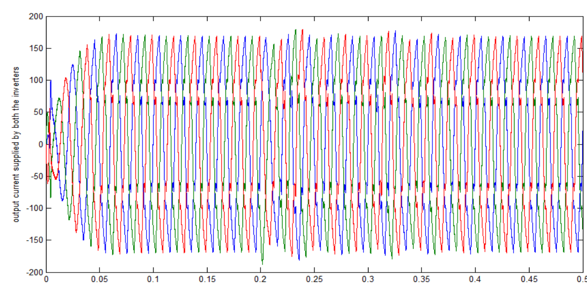

Figure. 22 output current supplied by both the inverters

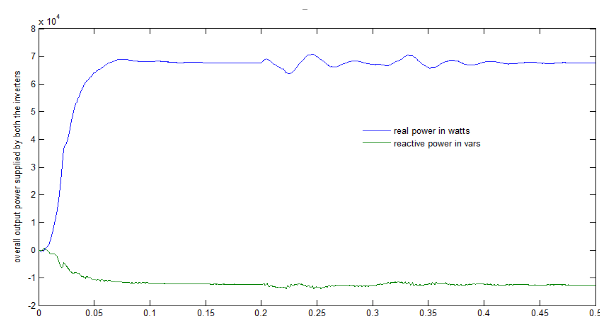

Figure. 23 overall output power supplied by both the inverters

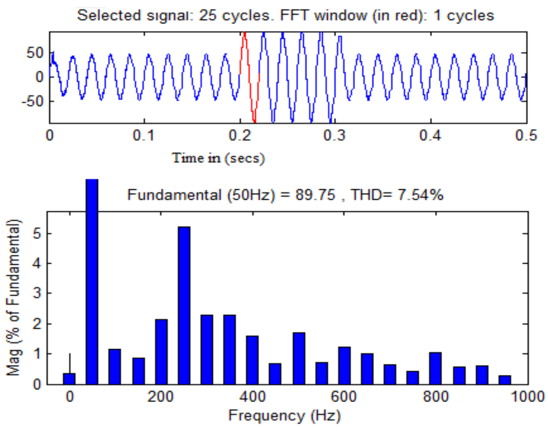

Figure. 24 total harmonic distortion of load current at the sudden increment of load condition is also world's acceptable range

Simulation results of ramp time control method:

Figure 25 shows the load voltage and load current waveforms with the ramp time current control method. Three phase RL load is in on condition from 0sec to 0.5 sec and consumes load current around 50 amps, suddenly another RL load with same rating is switched on from 0.2 sec to 0.3sec and consumes the load current of 50 amps.

Figure 26 shows the overall current supplied to the load is around 50 amps from 0 sec's to 0.2 sec's at 0.2 sec's suddenly another load with same rating is switched on that's why current consumed by the load is increased from 50 amp's to around 100amp's.

Figure 27 shows the voltage waveform at the point of common coupling maintains around 500 volts.

Figure 28 shows the real and reactive powers supplied to the load , from 0 sec's to 0.03 sec's the load is increasing continuously and reaches to 20kw with small transients, at 0.2 sec's due to the sudden increment of load waveform reaches to 40kw and then at 0.3 sec's again the load is switched off , wave form reaches to 20kw again and maintains at that point only. When compare with PI controller method ramp time controller follows the load accurately due to its fast response and follows the reference accurately.

Figure 29 shows the real and reactive powers injected to the grid. Here ramp time controller delivered the cleanest load power and grid power due to its ability to follow the reference closely.

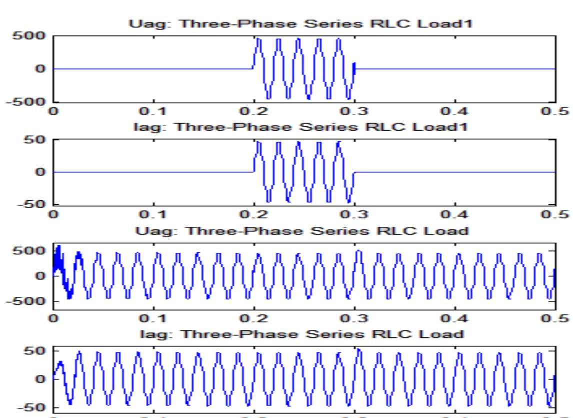

Figure. 25 load voltages and current of RL loads

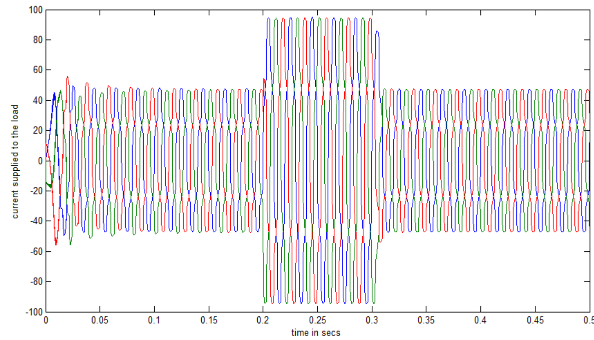

Figure. 26 Current supplied to the load

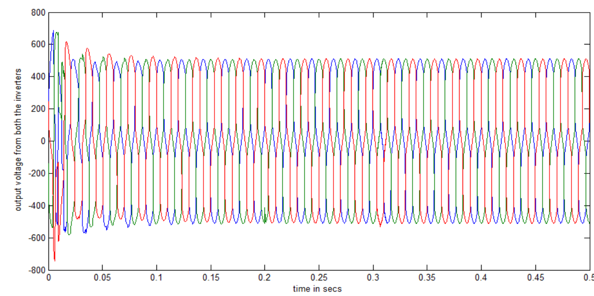

Figure. 27 output voltage from both the inverters

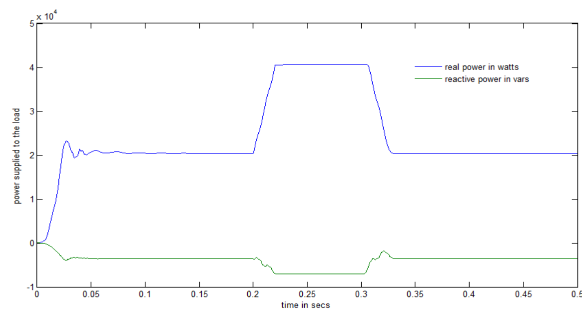

Figure. 28 Real and reactive powers supplied to the load

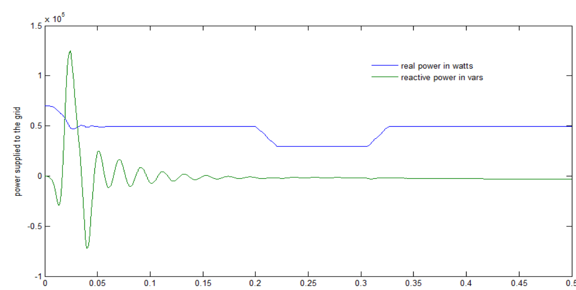

Figure. 29 Power supplied to the grid

6. Conclusion

Two current control methods which are used for DG applications are designed and validated with matlab simulink software. Three phase voltage source inverter is used to develop a simulation model for a grid connected DG source based system. A dq transformed PI current controller, ramp time current controller are used to generate the switching pulses for the inverter to control real and reactive power delivered from DG sources to the utility grid. The validity of the proposed controllers are analyzed and the results shows that the designed system

is capable of load following and maintains stability under sudden switching of load. But when compare the two methods ramp time controller gives better results due to its ability to follow the reference exactly.

7. References

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